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Cerenkov Scintillation Counter Measurements of the Intensity and Modulation of Low Rigidity Cosmic Rays and Features of the Geomagnetic Cutoff Rigidity

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Abstract. The primary cosmic radiation has been measured with a Cerenkov scintillation counter at various times in the solar cycle at locations having nominal cutoff rigidities of 0.8, 1.6, and 2.7 bv. Results are used here to delineate spectral features of low rigidity protons and α particles and to examine the rigidity and charge dependence of the eleven-year solar modulation. Details of particle transmission near the geomagnetic cutoff are also examined. The measurements indicate: (1) The observed nonsharp cutoff appears to be primarily due to expected transmission effects in a dipole-like field and to instrumental effects, and the actual cutoff is quasi-sharp in the Störmer sense. This is true even though the observed cutoff may be reduced to half that to be expected from the internal field, presumably because of external current systems flowing in the magnetosphere and its boundary. (2) The rigidity dependence of the eleven-year modulation of protons and that of α particles are closely similar above $\sim$1.2 bv. None of the presently proposed models for this modulation agree with our results. The implications of this lack of agreement are discussed, and it is concluded that certain general features of particle motion in the interplanetary medium not considered in present models may be of importance. One such general feature may be diffusive deceleration in the radially expanding interplanetary medium, which is shown to have the same effect as a static heliocentric electric field. (3) The differential spectrum of galactic cosmic rays near sunspot minimum at about 1-bv rigidity is either flat or falling slightly toward lower rigidities. The measurements in the rigidity range below 1 bv are compared with recent observations in this range.

Introduction. A detailed knowledge and comparison of the galactic cosmic ray proton and α-particle spectra at low rigidities (<2 bv) at various times in the solar cycle is essential in any attempt to select one of the various solar mechanisms proposed in recent years to account for the modulation of the primary radiation. In addition, a study of these spectra at sunspot minimum, when solar modulation effects are small, should provide information about the origin of cosmic rays and their propagation to the earth.

A number of difficulties arise in obtaining and interpreting such spectra. These are:

1. Secondary proton albedo effects, both upward-moving (splash) and downward-moving (re-entrant), may contribute a significant background of low energy protons that do not reflect the true primary spectrum.

2. Low rigidity protons are directly produced in the atmosphere above the detector.

3. Solar cosmic rays, both protons and α particles of low rigidities frequently present near the earth, are superimposed on the galactic cosmic ray spectrum.

4. Where the geomagnetic cutoff is greater than instrumental cutoff effects, it may seriously modify the shape of the measured spectrum, not only because of the uncertainty of what geomagnetic cutoff to apply to a particular location, but also because the transmission of particles through the earth's field is not experimentally observed to have a sharp cutoff.

Early (1955–1959) in the solar cycle now being completed, *McDonald* [1956] and *McDonald and Webber* [1959] extensively surveyed the spectra and galactic cosmic ray spectral changes at low rigidities. The details of

this survey are important for comparison with more recent measurements of the proton and α-particle spectra, and particularly with measurements made near the preceding sunspot minimum in 1954 and the one approaching in 1965.

The McDonald and Webber measurements of interest here were made during 1955–1956 at Minneapolis, where the problems connected with the geomagnetic cutoff and its effects on measured spectra are severe. In fact, these spectral measurements were used originally to define the geomagnetic cutoff existing at Minneapolis in an era when such measurements were of great value in understanding the influence of the nondipole terms in the earth's field on the cutoff [*McDonald and Webber*, 1959].

At that time it was not clear whether the spectra of protons and α particles measured were the spectra actually existing outside the earth's magnetic field, although it was obvious that features of the low rigidity end of the primary proton spectrum were being measured. We noted that the measured spectra were not consistent with the observations of *Neher* [1957] and of *Winckler and Anderson* [1957] who, from their intensity-altitude data and studies of the latitude effect at balloon altitudes above 51°N, found evidence of a larger flux of low energy particles at that time in the solar cycle (see also *Webber* [1962]). It was also not clear how the cutoff influenced the character of the solar modulation as deduced from several flights at the same latitude, although the cutoff was assumed to operate the same way on all flights. Thus a simple ratio of differential intensities at different times should be a measure of the true solar modulation effect.

With this background information, several observers have recently reported measurements of the low rigidity ends of the primary proton and α-particle spectra. These measurements, made since the last of the McDonald and Webber flights in 1959, and showing features of the spectra during the period of decreasing solar activity, have attracted attention particularly to the problems associated with measuring and interpreting the low rigidity end of the proton spectrum. They have, in fact, provided a picture that is inconsistent with the earlier McDonald and Webber results if these latter measurements are interpreted as the true primary proton spectra outside the earth's field.

Vogt [1962] and *Meyer and Vogt* [1963] recently reported intensities of low rigidity protons during 1960 and 1961 which considerably exceed those measured earlier by McDonald and Webber. The measurement by McDonald and Webber was made close to solar minimum at a time when the intensity of high rigidity (>1.5 bv) protons was actually greater. Such a modulation would appear to be inconsistent with the accepted pictures for the modulation of primary cosmic rays in a solar environment. Vogt and Meyer have interpreted this excess as possibly due to a steady solar particle emission at low rigidities or as due to protons ejected by large flares and stored for long periods in interplanetary space. Other measurements made during this later period with emulsions and counters [*Fichtel et al.*, 1964; *Bryant et al.*, 1962] suggest a proton spectrum somewhere between that of Vogt and Meyer and the earlier McDonald and Webber results.

To aid in the understanding of solar modulation effects and to focus attention on the problems associated with the measurement and interpretation of the low rigidity proton spectrum, we report here the results of a balloon flight that carried a Cerenkov scintillation counter detector above International Falls in September 1956. Preliminary results of this flight have been reported elsewhere [*Webber*, 1962]; more detailed results are presented here, and their implications are discussed. The fact that this flight was made when the primary cosmic ray intensity had decreased only slightly from its sunspot minimum value and where the geomagnetic cutoff is appreciably lower than at Minneapolis are of great importance in interpreting these data. In fact, the data are used to determine the transmission features of the earth's field at rigidities near the cutoff value at quiet times near Minneapolis, as well as to determine more appropriate values for the low rigidity part of the primary spectra of protons and α particles near sunspot minimum. In particular, it will be argued that interpreting the spectrums measured by McDonald and Webber at Minneapolis as the spectra of galactic particles existing outside the earth's field (or, what is equivalent, comparable to measurements at higher geomagnetic latitudes) is not correct.

Experimental results and comparison with

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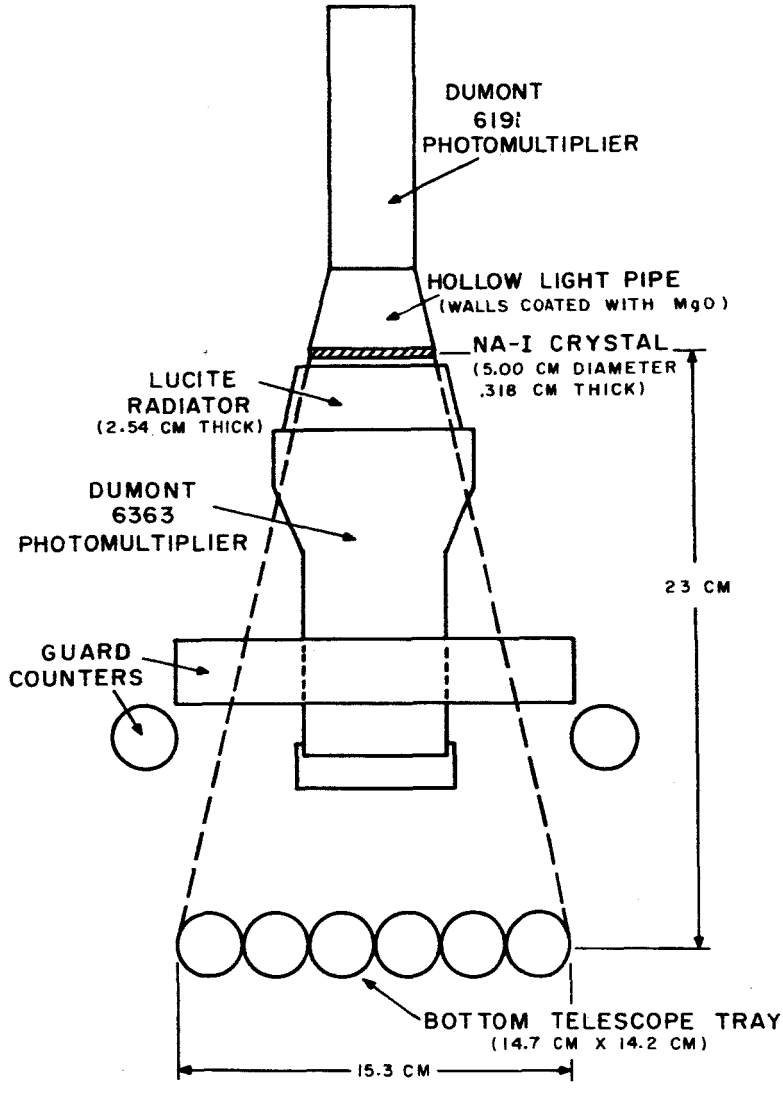

Fig. 1. The basic Cerenkov scintillation counter telescope.

other measurements. The instrumentation used at International Falls is identical to that used in all other flights of this series, including those at Minneapolis, and has been described in detail [*McDonald*, 1956; *McDonald and Webber*, 1959]. Briefly, it consisted of a three-element telescope containing a NaI crystal scintillation counter, a lucite Cerenkov detector, and a Geiger counter tray (Figure 1). The NaI crystal and the Geiger counter tray are the defining elements of the telescope. For each particle which traverses these elements, the outputs from the Cerenkov counter and the NaI crystal are recorded. A notation is also made when a telescope event is accompanied by the triggering of more than one counter in the tray or of one of the systems of guard counters. The data, which are recorded on a continuously moving film with a superimposed time base, consist of a pulse height from the NaI crystal and the Cerenkov detector for each event. The energy calibration is obtained by measuring the most probable energy loss for α particles and protons at minimum ionization, $(E_\alpha)_{\min}$ or $(E_p)_{\min}$, in both detectors. The selected intervals of ionization or Cerenkov loss are thus defined in terms

TABLE 1. Details of Balloon Flights

Date	Average Altitude, g/cm²	Average Cutoff Rigidity, bv	Bihourly Rate			
			Mt. Wash.	Climax	Mt. Norikura	Huancayo
September 7, 1956; International Falls, Minn.	6.5	0.8 ± 0.1	2340 −1.8%	6430 −1.3%	4155 −0.8%	
August 21, 1956; Minneapolis, Minn.	5.5	1.5 ± 0.1	2302 −8.1%	6356 −9.0%	4122 −3.2%	5380 −3.2%
June 2, 1959; International Falls, Minn.	5.0	0.85 ± 0.1	2112 +2.4%	5770 +2.8%	3994 +0.3%	5208 +0.8%
July 8, 1961 [*Fichtel et al.*, 1960, 1964]		0.2	2165 −1.6%	5934 −1.7%	4003 0.0	5250 +0.5%
August 6–8, 1961 [*Meyer and Vogt*, 1962, 1963]	5.0	0.2	2130	5840	4002	5278

of $(E_a)_{min}$ or $(E_p)_{min}$ and are matched to the corresponding kinetic energy and corrected for energy loss by ionization to the top of the atmosphere.

The corrections necessary to deduce a true intensity of primary particles at the top of the atmosphere have been discussed in detail by *McDonald and Webber* [1959]. Making these corrections, particularly those for secondary protons produced in the atmosphere and for splash and re-entrant albedo, is greatly facilitated by examining the pulse height distributions in five-minute intervals as the balloons rise to altitude. The intensities of protons and α particles in each energy interval can thus be obtained as a function of altitude. The relatively large geometric factor of the telescope used (7.2 g/cm²) and high altitude attained (5–6 g/cm²) greatly enhances this method of analysis.

The same two instruments, unchanged in any way, were used for all flights in the series. A standard set of corrections was applied to all flights, this set of corrections having evolved over the series of flights at a variety of latitudes. This standardization makes possible direct comparison of measured results, in particular, changes in intensity, with a high degree of accuracy, although absolute intensities could be subject to systematic errors.

The flight to be discussed here was launched on September 7, 1956, at International Falls, Minnesota. The average floating altitude of the equipment was 6.5 g/cm² (the telescope itself had an additional 8.8 g/cm² of material) at a geomagnetic latitude of 59.5 ± 0.2°, with a corresponding Störmer cutoff rigidity of 0.8 ± 0.1 bv, according to the most accurate estimates based on the earth's internal field [*Quenby and Wenk*, 1962]. Pertinent details about this flight and others that we will use in our comparison are shown in Table 1.

Preliminary examination of the data from the flight of September 7, 1956, while it was at altitude revealed two unusual decreases of approximately 20 per cent in the counting rate. The rate after the second decrease remained at the lower value, within experimental errors, for the rest of the flight. The indications were that two of the six Geiger counters in the tray had ceased to function, thereby reducing the effective area of telescope. Because of this possible uncertainty in the geometric factor, the data from this flight were not reported in the earlier analysis [*McDonald and Webber*, 1959].

A careful analysis of events that occurred during this flight revealed the following situation. The equipment performed normally while the balloon was rising to its peak altitude. Shortly after it reached peak altitude, the counting rate suddenly changed by 15 to 20 per cent within about 15 minutes. This rate remained constant for a few hours, then the counting rate dropped another 15 to 20 per cent within 15 minutes. The rate remained at this lower level (65 to 70 per cent of the initial rate)

TABLE 2. Proton and α-Particle Intensities Measured on September 7, 1956

Particle and Rigidity Range, bv	Integral Intensity, particles/m² ster sec	Differential Intensity, particles/m² ster sec Mv
Protons		
>1.2	2030 ± 70	
1.0–1.2		0.63 ± 0.05
0.83–1.0		0.60 ± 0.06
0.72–0.83		0.60 ± 0.06
0.64–0.72		0.46 ± 0.06
0.58–0.64		0.52 ± 0.09
0.54–0.58		0.40 ± 0.12
α Particles		
>4.5	86 ± 6	
3.0–4.5		0.029 ± 0.03
2.5–3.0		0.043 ± 0.05
2.0–2.5		0.071 ± 0.07
1.8–2.0		0.100 ± 0.09
1.6–1.8		0.123 ± 0.12
1.4–1.6		0.106 ± 0.10
1.2–1.4		0.088 ± 0.09
>1.2	290 ± 20	

until the end of the flight. These rate changes were consistent with the fact that 2 of the 6 Geiger counters in the telescope tray had ceased to operate. Such a failure would be expected to affect only the geometric factor of the telescope, not the pulse height distribution. Examination of pulse height distributions before and after the changes in counting rate revealed no change in the distribution of pulse sizes. Upon recovery of the instruments, it was found that two Geiger counters were inoperative. Thus the data are believed to represent a true measure of the spectrum of incident particles. A more accurate geometric factor for the telescope was deduced independently by comparing the counting rates of the relativistic protons and α particles with those obtained under normal conditions when the sea level neutron monitor rates were at approximately the same level as for the September 1956 flight. This further confirmed the fact that the telescope geometric factor during the flight was 65–70 per cent of the original value.

The differential intensities of primary protons in the rigidity range 0.54 to 1.20 bv and α particles in the range 1.20 to 4.5 bv deduced at the top of the atmosphere on September 7, 1956, are shown in Table 2 and in Figure 2. Also listed in Table 2 are certain integral intensity values for protons and α particles. The α-particle data in Figure 2 have been multiplied by 7.2 so that they can be directly compared with the proton values. These results are compared with results of two other flights in this general series; for this reason the data from the August 21, 1956, flight launched at Minneapolis are shown in Figure 2. The data from this flight have frequently been used as a measure of the intensity of low rigidity protons existing near the earth at sunspot minimum. These two flights are used to determine the features of the cutoff at Minneapolis.

In Figure 3 the data from a flight on June 2, 1959, also made at International Falls, are presented. The results of the International Falls flights in 1956 and 1959, when high latitude neutron monitors recorded a 10 per cent decrease in counting rate, are compared, and features of the eleven-year modulation of primary cosmic rays near the earth are discussed.

Features of the geomagnetic cutoff. During the two weeks between August 21 and September 7, 1956, the primary intensity, as measured by high latitude neutron monitors, changed by only 1.5 per cent. Any major difference in the spectra of protons and α particles measured on these two dates might then reasonably be attributed to a difference in cutoff rigidity at the two locations. It is believed that these data were not affected by the very small solar proton event on August 31, 1956 [*McCracken*, 1959]. In particular, we might at this time expect to define certain features of the cutoff rigidity existing near Minneapolis. Examination of Figure 2 reveals a sharp divergence of the two spectra at rigidities less than 2 bv, although the two spectra are identical above this rigidity within experimental errors. This divergence is noted for both protons and α particles and is grossly unlike any solar modulation process observed during this series of measurements. If the data are adjusted for the modulation that would be expected to accompany a 1.5 per cent change in the counting rate of a high latitude neutron monitor, and if we take the ratio of the differential intensities measured near Minneapolis and near International Falls, the results shown in Figure 4 are obtained. If these results are to be interpreted as the effect of a geomagnetic cutoff,

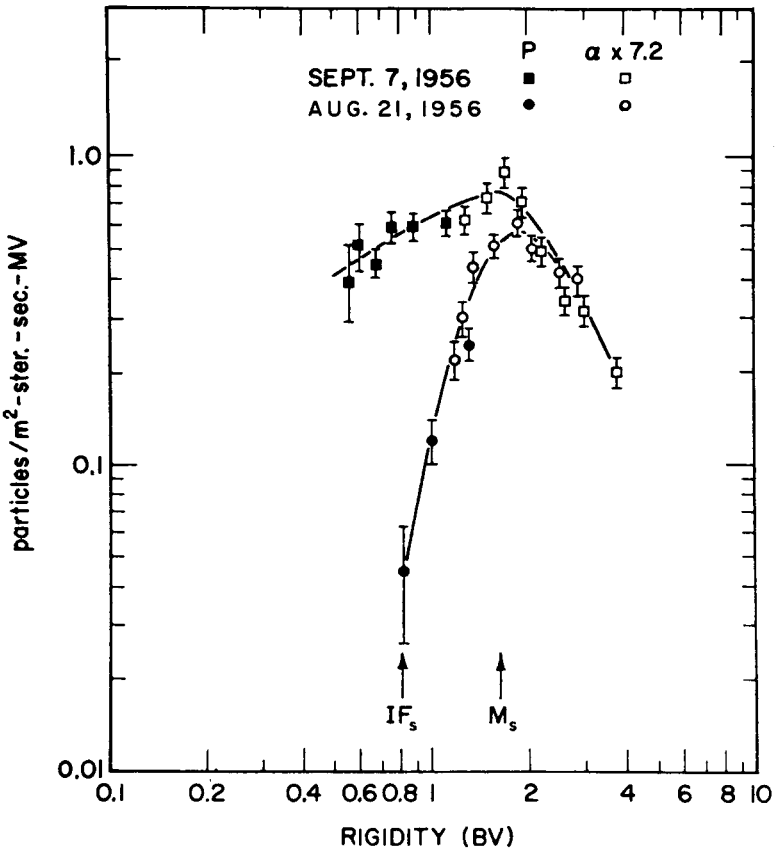

Fig. 2. Differential proton and α-particle intensities measured at International Falls on September 7, 1956, and at Minneapolis on August 21, 1956. Nominal Störmer cutoff rigidities at locations of flights are shown by arrows. α-particle intensities are multiplied by 7.2.

then, indeed, they do not fit the usual concept of a relatively sharp cutoff. However, before we discuss this in greater detail, a few preliminary remarks should be made.

Neither flight, at peak altitude, was exactly over Minneapolis or International Falls. The Minneapolis flight floated over southern Minnesota at an average cutoff rigidity of 1.6 ± 0.1 bv according to *Quenby and Wenk* [1962]. The International Falls flight floated over southern Ontario at an average cutoff of 0.8 ± 0.1 bv. Thus the cutoff difference is actually much greater than the difference between Minneapolis (1.35 bv) and International Falls (0.90 bv).

Observations at other periods in the sunspot cycle have revealed that the effective geomagnetic cutoffs associated with geomagnetic activity are frequently lower than those deduced only from the earth's internal field [*Winckler et al.*, 1961]. This may be true at geomagnetically quiet times as well [*Webber*, 1962; *Kellogg and Winckler*, 1961]. Such a lowered cutoff may be caused partly by a ring current of trapped protons having energies less than 1 Mev precessing in the earth's field. In view of the present understanding of these trapped protons, such a ring current may be a more or less persistent feature of the earth's magnetosphere during most, if not all, of the sunspot cycle. From a recent study covering the period 1959–1961, *Webber* [1963] has found that the average effective quiet time cutoff rigidity near Minneapolis is about 0.7 of that to be expected from the internal field only. If we associate this cutoff with the Störmer cutoff, it might be expected that a cutoff of about 1.1 bv would be appropriate for the Minneapolis flight and about 0.55 for the International Falls flight.

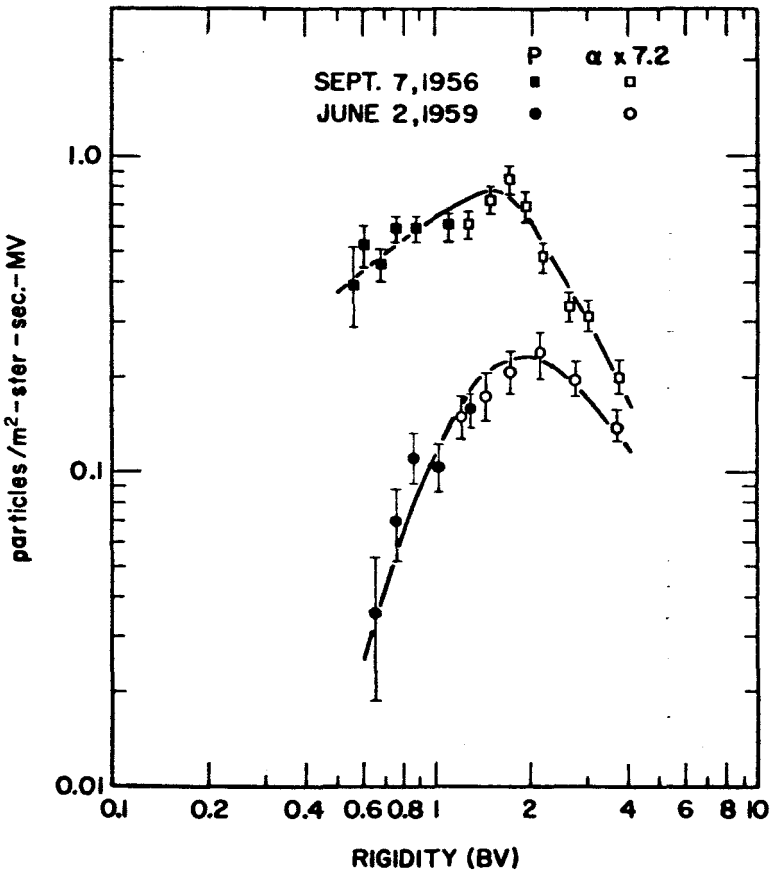

Fig. 3. Comparison of differential proton and α-particle intensities measured on two flights at International Falls: September 7, 1956, and June 2, 1959. α-particle intensities are multiplied by 7.2.

Turning to the interpretation of the data presented in Figure 4, we have represented the so-called transmission of the earth's field as a function of rigidity by the formula

$$T = \exp\left[-\frac{(P_c - P)}{P_0}\right]$$

where P_c is the rigidity, $T = 1$ (not to be confused with the Störmer cutoff), and P_0, the shape parameter of the cutoff, equals 260 ± 30 Mv in the present measurement. Such a representation is not claimed to have any physical meaning and is used merely to facilitate comparison of these results with those of *Earl* [1962] and *Freier* [1962], who have measured the transmission near the cutoff at Minneapolis during the incidence of solar protons in a magnetically active period.

On the basis of Störmer theory and Liouville's theorem, it is known that in a given direction at a given instant the transmission of particles through the earth's field drops sharply from 1 to zero at a value known as the Störmer cutoff rigidity. In any experiment, however, idealized conditions cannot be attained. Further, there are experimental errors inherent in the measurements of rigidity, and, finally, there are transmission effects in the earth's field itself (penumbral effects), all of which tend to smear out what in reality may be a sharp Störmer cutoff. Keeping in mind the earlier discussion of the variability of the Störmer cutoff itself, we shall attempt to evaluate some of the effects that could smear the cutoff and see if they are compatible with the measurements shown in Figure 4. These effects include:

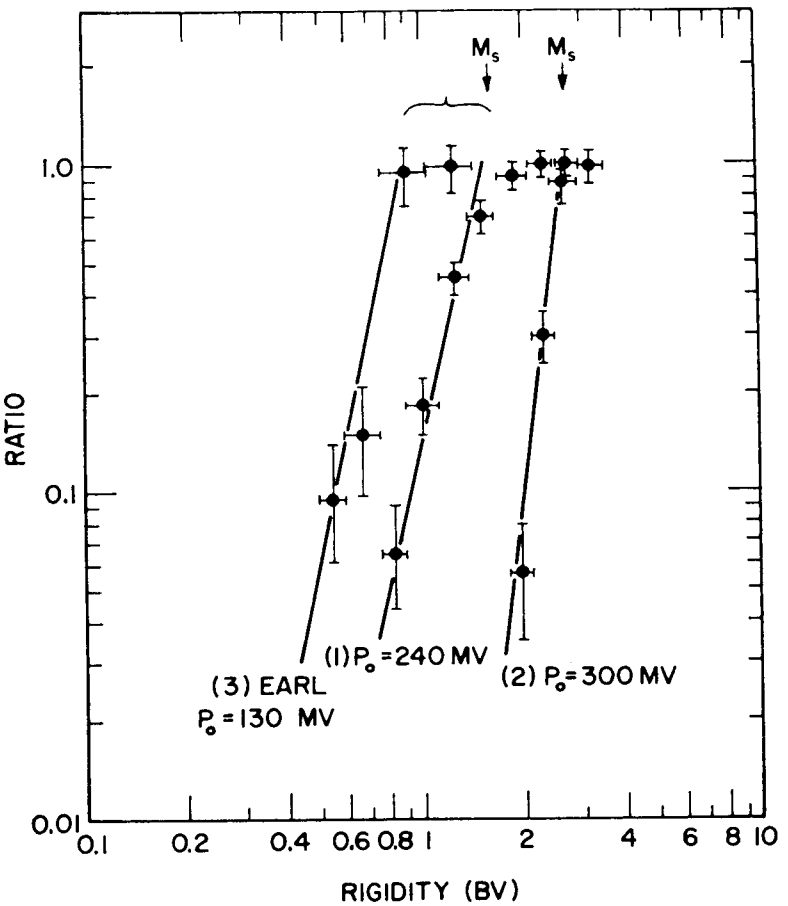

Fig. 4. Fraction of particles transmitted through the earth's field as a function of rigidity near the Störmer cutoff rigidity at various latitudes.

1. The penumbral effects in a dipole field. For values of the Störmer constant $\gamma < 0.93$, all orbits are allowed and relatively simple; for $\gamma > 1.00$, all orbits are forbidden. For $0.93 \leq \gamma \leq 1.00$, the orbits are very complex, and it is necessary to delineate the allowed and forbidden values of γ in this range which correspond to allowed and forbidden rigidities in a particular direction only. The width of this region of partial transmission corresponding to the above range of γ is 15 per cent of the Störmer cutoff rigidity; e.g., in the vertical direction $P_c = 14.9 \cos^4 \lambda/\gamma^2$. Although it is generally assumed that there is nearly perfect transmission in this penumbral region at latitudes greater than 50°, a careful study of the orbit calculations of *Störmer* [1955], *Schwartz* [1959], and *Kasper* [1959] reveals a systematic and clearly defined series of forbidden γ in the region of latitudes greater than 55°. These values of forbidden γ corresponds to perhaps 6 or 8 very narrow rigidity ranges in this penumbral region. These rigidity ranges become narrower, and some of them may vanish altogether, at higher latitudes. In a typical detector with a resolution of about ± 0.05 bv, these forbidden intervals (generally about 0.01 bv wide or less) will smear the cutoff rigidity slightly. This effect is shown in curve 1 of Figure 5 for a nominal Störmer cutoff of 1.1 bv and a detector resolution of ± 0.05 bv.

2. The experimental arrangement is such that the particles arrive at the detector over a finite range of angles. In our measurement the opening angle is $\pm 30°$ from the vertical, an angle that is also typical for the acceptance angle of emulsions and other counter devices.

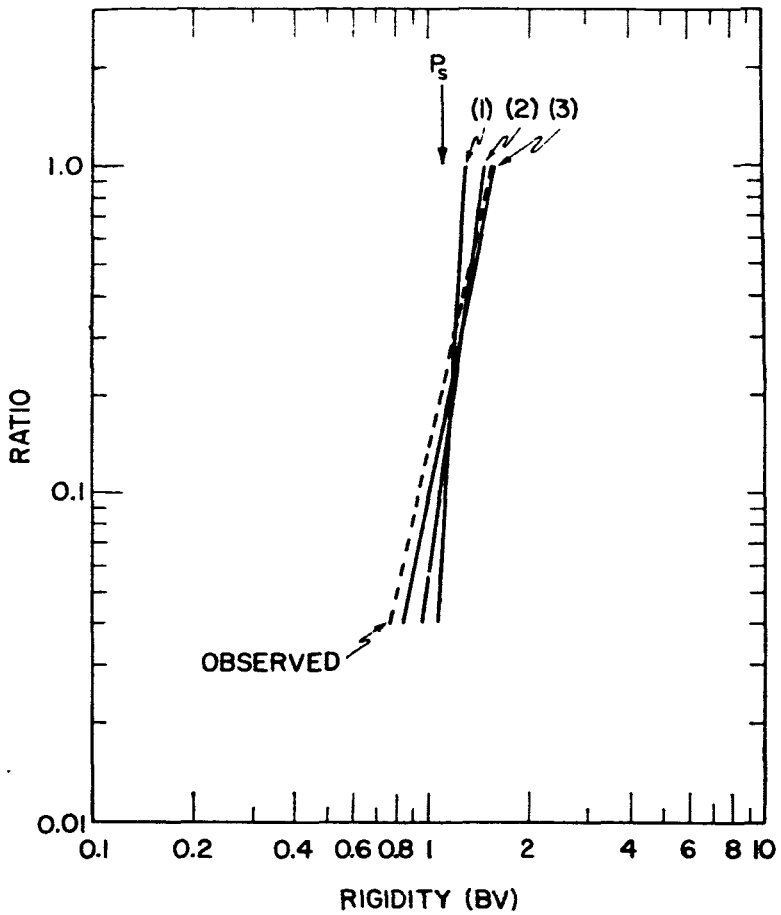

Fig. 5. Comparison of observed and predicted transmission of particles through the earth's field at rigidities near the Störmer cutoff rigidity.

Such an angle introduces a spread of cutoffs that can be deduced from

$$P_s = \frac{59.2 \cos^4 \lambda}{[1 + (1 - \sin \epsilon \cos \phi \cos^3 \lambda)^{1/2}]^2}$$

where λ is the geomagnetic latitude, ϕ the azimuth measured from east, and ϵ the zenith angle. For a Störmer cutoff of 1.1 bv and an opening angle of $\pm 30°$ from the vertical, this effect introduces extremes of ± 65 Mv from the mean cutoff.

3. In a balloon flight of a number of hours' duration, a drift of ± 25 miles from the mean geomagnetic cutoff is typical. Since the data are usually averaged over the whole flight, the drift may introduce a spread of ± 60 Mv at a cutoff of 1.1 bv. Curve 2 of Figure 5 shows the superposition of the aforementioned three effects, which are essentially geomagnetic.

In a very long observation period, a time-varying cutoff could seriously influence the measurements. Since the data were obtained during quiet periods, this effect is not considered.

There are also effects which are instrumental or which occur in the atmosphere above the detector. These include (1) Landau fluctuations in energy loss, both in the detector and in the atmosphere above the detector; (2) fragmentation of heavier nuclei into protons (or α particles) in the atmosphere above the detector (this effect [*Fowler et al.*, 1957] will principally contribute particles below the geomagnetic cutoff for protons and α particles); and (3) experimental uncertainty in energy or rigidity measurements.

Finally, a small intensity of unidentified deuterons or tritons or, in the case of α particles, unidentified He^3 nuclei would serve to diffuse the cutoff.

It is difficult to evaluate these effects analytically. In this study it is estimated that they would introduce a minimum uncertainty in rigidity of ± 10 per cent. A superposition of all the effects discussed above is shown in curve 3 of Figure 5. Comparison of this curve with the dotted curve representing the experimental data suggests that we can interpret the vertical cutoff at Minneapolis on August 21, 1956, as a relatively sharp Störmer cutoff at 1.0 to 1.1 bv. These measurements do not exclude a diffuse cutoff over the interval 0.9 to 1.1 bv.

To extend our study of the measured transmission of particles near the cutoff rigidity, we shall examine data from another flight. This was made from Moberly, Missouri, and floated at an average cutoff rigidity of 2.7 ± 0.1 bv [*Quenby and Wenk*, 1962]. The data from this flight, which have been published by *McDonald* [1959] and *Webber* [1962], are consistent with an effective cutoff rigidity of 2.25 ± 0.1 bv. This cutoff was determined by measuring the point of a sudden break in the α-particle differential spectrum. A determination of the primary spectrum from an International Falls flight is available for a time, one year later, when the counting rate of high latitude sea level monitors was within 1 per cent of the rate during the Missouri flight. Thus, if the ratio of differential intensities measured in Missouri and at International Falls is taken, the transmission curve shown in Figure 4 is obtained. The shape parameter of the cutoff in this case is given by $P_0 = 300$ Mv. Again, this is compatible with a quasi-sharp cutoff at 2.2 to 2.3 bv and a superposition of the instrumental effects discussed earlier.

Finally, these results (Figure 4) on the shape of the cutoff can be compared with those of *Earl* [1962] obtained near Minneapolis during the course of a solar cosmic ray event on September 4, 1960. Earl's measurements with a cloud chamber are consistent with a shape parameter $P_0 \sim 100$ Mv and a sharp Störmer cutoff at 0.55–0.60 bv. The cutoff was much below normal at Minneapolis at that time because of strong magnetic activity. In addition, because of the high intensity and steep spectrum of the solar particles, Earl could actually observe the change in cutoff during periods of less than one hour. The value of the shape parameter Earl obtained using solar cosmic rays is somewhat less than that obtained using galactic cosmic rays. However, this is to be expected for a number of reasons, one being, of course, that in the short time interval Earl used little balloon drift could occur. Earl's measurements also suggest that a better parameter for defining the experimental shape of the cutoff might be a relative shape parameter P_0/P_s, where P_s is the effective Störmer cutoff. For Earl's work this ratio is 0.18, and for our measurements 0.23 and 0.14 at 1.1 and 2.3 bv, respectively.

We have shown that our results can be explained by a sharp Störmer cutoff, and we believe that an intrinsic diffuse Störmer cutoff greater than ± 0.1 bv would manifest itself in our measurements. At Minneapolis this corresponds to an energy range for protons of 370 to 520, and we cannot rule out a diffuse cutoff over this interval.

Further, it appears that such a quasi-sharp cutoff exists, even though the cutoff may be reduced considerably below that appropriate to the internal field. The mechanisms responsible for the lowered cutoffs are thus limited to those that preserve motion in the earth's field in the Störmer sense. Specifically, such a cutoff would rule out an energy-dependent spatial diffusion through a disordered earth's outer field to positions where Störmer (or Alfvén) trajectories could be followed to the surface of the earth.

Before concluding this discussion of the features of the geomagnetic cutoff, it might be well to ask what, if any, are the effects of a cutoff on the measured spectrum of primary protons at International Falls presented in this paper. To obtain a useful answer to this problem, we recall that slightly south of Minneapolis, where the predicted Störmer cutoff is 1.6 bv, the measured transmission in the earth's field began to deviate from 1 about 1.5 ± 0.1 bv, and the data are consistent with a sharp Störmer cutoff of 1.0–1.1 bv. Most models for the change in cutoff due to external field systems suggest that the fractional change should not be a strong function of latitude between Minneapolis and Intenrational Falls. Thus, for similar conditions, the effective Störmer cutoff during the

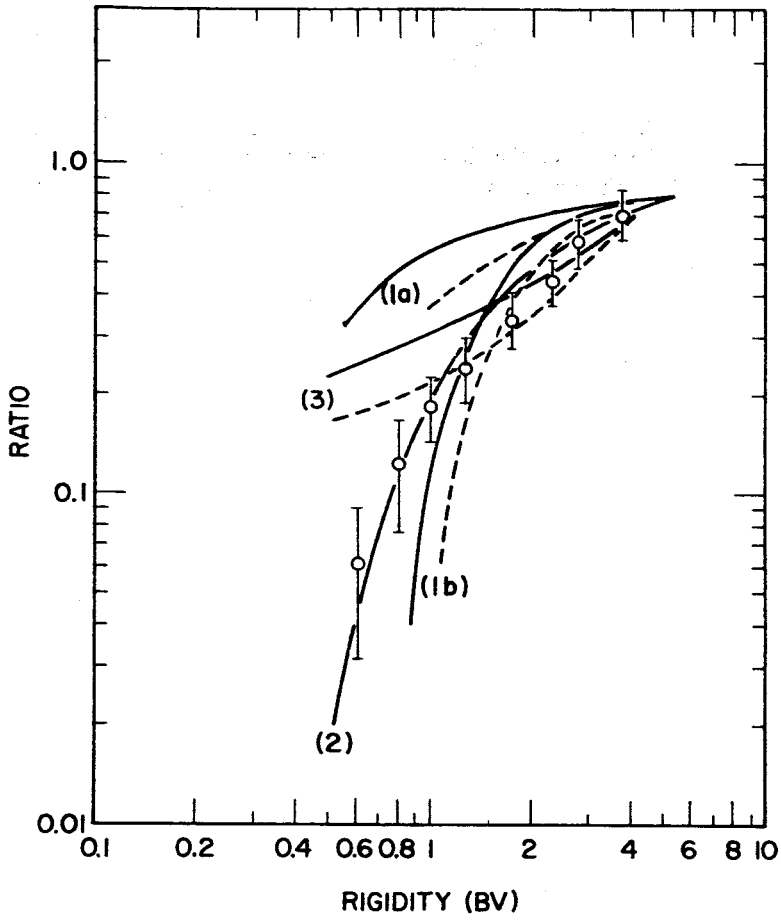

Fig. 6. The observed modulation of low rigidity primary cosmic rays during the solar cycle. Circles give the ratio of proton and α-particle intensities measured on June 2, 1959, to those measured on September 7, 1956, at International Falls. Curves 1*a* and 1*b* are two possible modulations according to *Parker* [1962], curve 2 is the modulation expected according to *Elliot* [1960], and curve 3 is the modulation to be expected upon passage through an electric field of 400 Mv.

International Falls flight might be expected to be approximately 0.5 bv and the effective transmission might begin to deviate from 1 at approximately 0.6–0.7 bv. If this happens, the experimental points below 0.7 bv may not represent the true primary spectrum near the earth. We shall consider the implications of this point in the next section.

The eleven-year modulation of the galactic cosmic rays and the primary spectrum at low energies. Although it is possible that the spectrum measured at International Falls does not represent the true primary spectrum below 0.7 bv, we believe that it is possible to compare two flights at this location to obtain useful information on the modulation of the low rigidity primary radiation during the sunspot cycle. This information should be accurate at rigidities above 0.7 bv and below this rigidity as well, provided that the features of the cutoff have not changed between or during the two flights. The measurements we wish to compare were made on balloon flights at International Falls on September 7, 1956, and June 2, 1959, when the counting rates of high latitude neutron monitors decreased by about 10 per cent because of the eleven-year variation in solar activity. The differential spectra measured on these two flights

are shown in Figure 3. The difference in these two spectra is believed to represent the features of the eleven-year modulation acting during this period. For convenience when comparing these curves with various theoretical models, we have taken the ratio of the differential spectra measured on the two flights and present this information in Figure 6. This ratio, then, should represent the fractional modulation during this period of the galactic cosmic ray spectrum as a function of rigidity in the solar environment. At least two features of the modulation are of great importance: (1) the form of the fractional modulation as a function of rigidity, and (2) the relative fractional modulation of protons and α particles at the same rigidity. Taking the second feature first, we note that the rigidity region in which the proton and α-particle differential intensity measurements overlap is extremely small, from 1.15 to 1.30 bv. In this rigidity range, during a period when the differential intensity decreased to approximately 20 per cent of its sunspot minimum value, there is no difference in the behavior of protons and α particle with an experimental error of approximately -15 per cent on the individual measurements. Considering rigidities greater than 1.3 bv, we can make less definitive statements on the behavior of protons and α particles up to at least 4.5 bv by comparing their integral intensities measured above selected rigidities at various times in the sunspot cycle, in the series of flights with the Cerenkov scintillation counter. These data have been examined in detail by *Webber* [1962], who has concluded that the proton and α-particle variations in this rigidity range due to the eleven-year sunspot cycle are consistent within ± 15 per cent.

To see how restrictive our data on the rigidity dependence of the fractional modulation and on the relative fractional modulation of protons and α particle are in terms of a model for the long-term, or eleven-year, modulation of the galactic cosmic rays, let us investigate a few of the recent models that, at least to a first approximation, appear to predict a modulation similar to that observed. These include (1) the solar wind model of *Parker* [1962], (2) the general solar dipole field model of *Elliot* [1960], and (3) the heliocentric electric field deceleration model suggested first by *Nagashima* [1953] and more recently by *Ehmert* [1960]. We shall compare the predictions of these models on the rigidity dependence of the eleven-year variation with our observations in some detail, beginning with Parker's solar wind model. The eleven-year variation we obtained corresponds to the quiet day intensity decrease discussed by Parker. For the fractional change in intensity as a function of rigidity, Parker obtains

$$\frac{\Delta j}{j_0} = \frac{4\Omega r \sin\theta}{W(1 + 4\gamma\Omega r^2 \sin\theta u_0 / VaW)}$$

a modulation not unlike that behind the blast wave which Parker suggests causes the Forbush decrease. In the above expression, Ω is the solar angular velocity, r the distance to which the spiral field surrounding the sun is assumed to extend, θ the angle between the lines of force and a radius vector from the sun, γ a geometrical factor probably less than 1, V the average velocity of the solar wind, W the velocity of the cosmic ray particle, a an inner reference distance near the base of the corona, and u_0 a drift factor depending on the characteristics of the assumed general solar (dipole) field. In essence, the decreased intensity is a result of two effects: an outward sweeping of the cosmic ray particles by the solar wind, which dominates at low rigidities and produces a fractional modulation $\Delta j/j_0 \sim 1/W$, and a drift in latitude across field lines from the polar regions into the equatorial plane (caused by gradients in the equatorial plane), which dominates at high rigidities and produces a fractional modulation

$$\frac{\Delta j}{j_0} \approx \left(\frac{Z}{A}\right)\frac{1}{K}$$

where a is taken to be about $2r$, $\sin\theta \sim 1$, $\Omega = 2.7 \times 10^{-6}$ rad/sec,

$$u_0 = \frac{1 \times 10^6}{Z}\,\frac{K(K+2)}{K+1}$$

and $V \sim 700$ km/sec near solar maximum. The other quantities are effectively unknowns and are determined by the modulation itself. We note that, as $\gamma \to 0$, $\Delta j/j_0 \sim 1/W$ and sweeping alone dominates. The modulation is constant at high rigidities and is in disagreement with experiment. The greater the value of γ, the lower the rigidity at which the drift term begins to dominate in the modulation.

First let us try to fit the data near the upper end of our measurements at 5 bv. Then we require that $\Delta j/j_0 = 0.22$, which means $K/W > 0.22$, and $r > 40$ AU. Suppose we take $r = 65$ AU; then $K/W = 0.35$, and $\Delta j/j_0 = 0.35/[1 + 120(A/Z)v]$ at 5 bv. For $A/Z = 1$, this gives $v = 5 \times 10^{-3}$, and the rigidity at which the two effects are equal is approximately 7 bv. The form of the modulation, which is essentially velocity dependent, is shown as curve 1*a* in Figure 6. Notice the separation of protons and α particles above 1 bv and the small amount of modulation below 2 bv, both of which are not in agreement with our results.

On the other hand, let us fit the observations at, say, 1 bv. Then $\Delta j/j_0 = 0.82$, which gives $r \sim 130$ AU. If we also require that $\Delta j/j_0 = 0.22$ at 5 bv, then $v = 1.5 \times 10^{-2}$ and the rigidity at which the two effects are equal is about 2 bv. This is a somewhat better fit and is shown as curve 1*b* in Figure 6. It still, however, shows a separation of protons and α particles above 1 bv which is greater than the experimental evidence indicates. It also predicts $\Delta j/j_0 > 0.99$ at $P \sim 0.9$ bv, which is clearly outside the range of experimental uncertainty.

In effect our results on the eleven-year variation do not agree with the modulation expected with Parker's solar wind model. Since the presence of a solar wind in the interplanetary environment has been clearly established [*Neugebauer and Snyder,* 1962], it would appear that effects other than those considered by Parker in this admittedly simplified treatment are important to the decrease of cosmic ray intensity. Later we shall discuss what some of these effects might be.

Turning now to the general solar dipole field model of *Elliot* [1960], we see that the fractional modulation can be expressed in the form

$$\frac{\Delta j}{j_0} = \left\{1 - \left[\frac{\pi_e{}^2 P}{45 M_s}\right]^{\alpha(P)}\right\}$$

where

$$\alpha(P) = \left[\left\{1 + 4K_1\left(\frac{P_0 + P}{P}\right)^2\right\}^{1/2} - 1\right] \Big/ 4$$

In this equation M_s is the dipole moment of the sun, P_0 is a quantity that is a measure of the strength of scattering centers and that gives a rigidity dependent scattering mean free path, and K_1 is a quantity that reflects the loss of particles into the solar surface. A study of the equation reveals the following effects of these three parameters: increasing or decreasing M_s (keeping α constant) increases or decreases the fractional modulation by a constant amount at each rigidity; increasing or decreasing M_s and decreasing or increasing α to obtain the same modulation at, say, 5 bv will, respectively, slightly flatten or steepen $\Delta j/j_0$ versus P. Varying M_s, however, changes the rigidity dependence of the modulation very little.

The parameters K_1 and P_0 are not independent. If we keep the modulation constant at 5 bv and increase K_1 (corresponding to greater absorption by the sun) and decrease P_0, the $\Delta j/j_0$ versus P is flattened. If we decrease K_1 and increase P_0, the rigidity dependence of the fractional modulation is steepened. The best fit to the data, which also corresponds to the observed 10 per cent decrease in high latitude neutron monitor counting rate, is shown as curve 2 in Figure 6; it is obtained with $M_s = 1.8 \times 10^{25}$ gauss cm^3, $K = 0.15$, and $P_0 = 2.4$ bv. This would correspond to a mean free path $\lambda_f \sim 10^{11}$ cm (independent of rigidity) of the particles in the diffusing region near the solar equatorial plane.

Notice that this model gives excellent agreement with the observed rigidity dependence of the fractional modulation. It also predicts the same modulation for protons and α particles (in agreement with experiment), primarily because of the influence of the general solar dipole field and the application of Störmer theory to the arrival of particles near the earth. The agreement with rigidity dependence is a result of having three parameters available for adjustment. The physical reality of these parameters is not always clear. In particular, it appears that K_1 is not calculated in a consistent fashion. While we cannot reject Elliot's model on the basis of cosmic ray evidence alone (indeed, it gives remarkably good agreement), we feel it has not yet been demonstrated that such a model can predict the required cosmic ray decrease near the earth when reasonable ideas of diffusion are used in the evaluation of the constant K_1.

Finally, we compare our results with the heliocentric static electric field modulation. Here the intensity change comes about because of

energy loss and the application of Liouville's theorem, which says that $D = J/P^2B$ is constant during the motion of the particles (D = density of particles in phase space, B = velocity). The form of the change in primary spectrum is given by

$$\frac{dj}{dE_e}(E - V) = \frac{dj}{dE_\infty}(E)\left\{\frac{(E - V)(E - V + 2)}{E(E + 2)}\right\}$$

where E and V are in bev, $(dj/dE_e)(E - V)$ is the differential intensity at the earth of particles with kinetic energy $(E - V)$, and $(dj/dE_\infty)(E)$ is the differential intensity of particles with energy E at large distances from the earth ($V = 0$).

Setting $\Delta j/j_0 = 0.22$ at 5 bv gives the potential $V = 400$ Mv and the fractional modulation shown in curve 3 of Figure 6. Note again the separation of protons and α particles and the modulation at low rigidities. The predicted proton–α-particle difference in fractional modulation reaches about 1.5 at low rigidities and is about 1.3 at rigidities between 1.0 and 1.5 bv where our proton and α-particle measurements overlap. Our results indicate that the modulation is the same in this region to within 10–15 per cent. The flattening of the modulation at low rigidities (primarily determined by the shape of the unmodulated spectrum at slightly higher rigidities) is not in accordance with our measurements.

In summary, our results are not in agreement with the concept of a static heliocentric electric field, although experimental uncertainties do not permit us to regard this as a very powerful statement.

None of the three models discussed above for the long-term, or eleven-year depression of galactic cosmic ray intensity appears to agree satisfactorily with detailed measurements of the rigidity and charge dependence of the changes occurring during a particular interval of the recent cycle. The most fundamental difficulty seems to be that the models predict a pronounced splitting of the proton and α-particle modulation, even above 1 bv, although this splitting is not observed above $\sim$1 bv. Also, the fact that the models cannot explain the observed rigidity dependence of the fractional modulation for protons alone suggests that perhaps some important feature of particle motion is not being considered in these models.

A number of other models have been proposed, and the problem seems mainly to be one of selecting which features of these models must be considered in understanding the eleven-year modulation. In this connection it is useful to use as a guide the recent direct measurements of the interplanetary field configuration and the recent detailed measurements relating to the propagation of the solar-flare-produced cosmic rays.

The direct measurements of the plasma [*Neugebauer and Snyder*, 1962] and magnetic field [*Coleman et al.*, 1962] on Mariner 1 are consistent with the concept that the interplanetary medium is moving outward, at relatively quiet times, with a velocity of about 400 km/sec. In addition, the Imp 1 data show the direction of the magnetic field to be primarily in the equatorial plane (N. F. Ness, private communication, 1964), and there is clear evidence from the Mariner 1 data of magnetic field and plasma variations of a character that would produce randomizing of the motions of cosmic ray particles. Such evidence points to a diffusion-like picture for at least part of the eleven-year modulation. The success with which the diffusion picture has been applied to the propagation features of solar cosmic rays [*Bryant et al.*, 1962; *Hofmann and Winckler*, 1963; *Webber*, 1963] also gives support to this idea.

Such a model has been invoked to explain the eleven-year variation by *Parker* [1958], who solved the steady state diffusion equation with convection,

$$\nabla\cdot(\mathbf{V}j) = \tfrac{1}{3}\nabla\cdot(\lambda\nabla(wj)$$

with some rather simple assumptions about the behavior of V, the outward velocity (convection) of the interplanetary medium, and λ, the effective mean free path between collisions (j is the density of particles, w their velocity). With the assumptions that no energy change occurs and that V is constant and radial, two solutions can be found: (1) If the features of the individual scattering centers are such that $lB \gg \rho B$ (l = scale of scattering centers, ρ = radius of curvature of a particle in field B), then

$$j, (r, E)/j(\infty, E) = \exp^{-\text{const}/W}$$

and (2) if the features of the individual scattering centers are such that $lB \ll \rho B$, then

$$j_2(r, E)/j(\infty, E) = \exp^{-\text{const}/WP^2}$$

where P is the particle rigidity. This simple form is obtained if we assume only one scale of inhomogeneities (i.e., l = constant), and the constants in the above equations are then determined by values chosen for l, B, V, and the dimensions of the disordered region around the sun [*Parker*, 1958]. Both solutions should be joined at some rigidity roughly equivalent to $PB \approx lB$; thus there will be a kink in the actual modulation owing to the simplifying assumptions about the scattering process [*Parker*, 1962].

Let us compare the experimental data with such a model. First we can use the best estimates of the average values B and V from space probe data; e.g., $B \sim 1 \times 10^{-4}$ G (in irregularities), and $V \sim 700$ km/sec (near solar maximum).

The value of B determines the point at which the two solutions are joined as $\mathbf{P} \sim 1/35$. For the value of $l \sim 2 \times 10^{11}$ cm used by *Parker* [1958], $\mathbf{P} \sim 6$ bv. The modulation at low rigidities is thus about $1/W$, and we have seen in discussing Parker's solar wind model that this is much too flat (curve 1*a*, Figure 5). We must thus attempt to deduce a more reasonable effective value of l. Evidence collected by *Webber* [1963] on the propagation of solar cosmic rays suggests that a possible break in the effective mean free path λ occurs at a rigidity of about 1.6 bv. Below this rigidity λ seems to be roughly a constant $\sim 2 \times 10^{12}$ cm, whereas above this λ appears to vary with energy, although its energy dependence cannot be determined. If we take 1.6 bv as the point at which the scattering process changes character in Parker's simple description, then l becomes $\sim 5 \times 10^{10}$ cm (recall that in Elliot's model a value of $1 \sim 3 \times 10^{10}$ cm is necessary). The modulation will change from a form $\sim l/W$ to a form $\sim l/WP^2$ at this rigidity. It is in fact very similar to the modulation obtained with Parker's solar wind model, except that in this case it falls off more rapidly at high energies. Therefore, it is a rather poor fit to our results at both ends. In fact, such a strong rigidity dependence at high energies is clearly incompatible with the long-term modulation observed by neutron monitors.

In spite of these difficulties, it seems that we should seriously consider the features of a diffusion-like model for the eleven-year modulation based on the solar cosmic ray observation. The theory as presently developed is in a most elementary form. The scattering process has been treated in a very simple way. In addition, the variation of λ with r and a distribution of scattering center sizes must be considered. The possible energy change in such a medium has not yet been considered in a workable form. We recognize that the modulation resulting from this diffusive deceleration in an expanding medium is much like that from a static electric field. It may be significant that the electric field modulation, with only a single adjustable parameter, can adequately fit the data over a very wide range and in fact predicts the dependence of the modulation observed at high energies (>10 bv).

The relation between a diffusive deceleration picture and a static electric field is even more intimate than is suggested by the similarity in the modulations. It can be reduced to the fundamental collision of a particle with a magnetic inhomogeneity which, in the case of the expanding medium, results in the inverse Fermi effect. The acceleration (or deceleration) in an individual scattering is caused in the last analysis by the induced electric field $\mathbf{E} = -(1/C)\,\mathbf{U} \times \mathbf{H}$, which is due to the velocity $\mathbf{U}$ of the scattering systems relative to the rest system in the solar system (e.g., the earth). This general feature of accelerating (or decelerating) mechanisms has been pointed out by *Parker* [1958]. *Laster et al.* [1962] have applied the diffusive deceleration picture to expanding magnetized clouds moving outward from the sun and suggest that these effects may dominate in the production of the Forbush decrease. We shall illustrate the basic idea by a specific example and note that the change in energy of the particle after reflection from a moving inhomogeneity is simply $\Delta\epsilon = Ze \int \mathbf{E} \cdot \mathbf{dS}$, where $\mathbf{dS}$ is measured along the path of the particle. Consider a particle moving toward a scattering center with velocity $\mathbf{V}$, the scattering center having a velocity $\mathbf{U}$, small compared with $\mathbf{V}$, and in the same direction as $\mathbf{V}$. If we assume the particle is spiraling around $\mathbf{H}$ and moving into a region of increasing field, $\mathbf{E}$ will oppose $\mathbf{V}$. Then $\Delta\epsilon = 2Ze(\mathbf{E})r \sin \theta$,

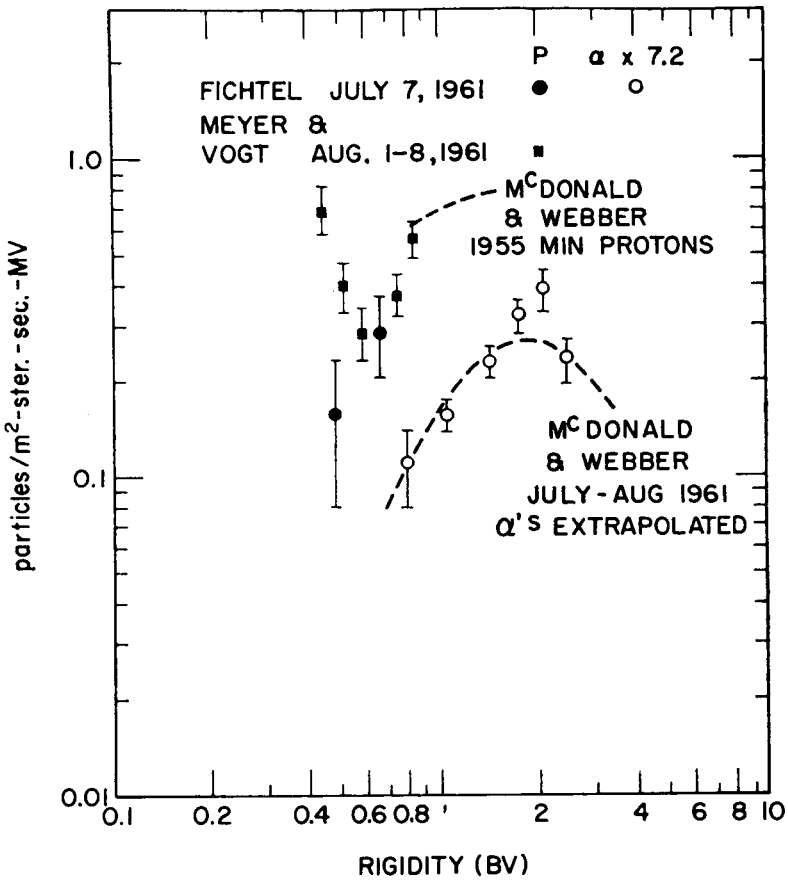

Fig. 7. Comparison of predicted proton and α-particle intensities according to regression curves of *McDonald and Webber* [1962] (dashed lines) and those measured at comparable times during July and August 1961 by other observers. Note the apparent excess of low rigidity protons as measured by these observers and the good agreement for the α particles (lower dashed curve). Upper dashed curve refers to proton intensity reported in this paper and measured at a time when the neutron monitor rate was near its sunspot minimum value and about 10 per cent higher than at the time of the July-August proton measurements shown.

where $r = \epsilon V\gamma/ZeHc$, $\epsilon = mc^2$, $\theta = (\pi/2) - \psi$, and ψ is the pitch angle of a particle. Thus $\Delta\epsilon/\epsilon = -UV/c^2$, a decrease in total energy which is precisely equal to that obtained using the conservation of energy and momentum in an elastic collision with a moving wall. This change occurs only in the longitudinal component of the momentum; the transverse component first increases and then decreases to its initial value during the course of the collision.

The summation of many such collisions will have the equivalent effect of a net decelerating potential without the necessity of a very large uniform electric field near the sun. It is true that, at a particular location in the expanding region, particles will be found with a distribution of energy losses as opposed to the constant energy loss in the static field case; however, the effective modulation should be very similar and should be deduced by the approach of *Laster et al.* [1962].

We believe that, in trying to disentangle the effects of diffusion, energy loss, convection, drift, and other possible general characteristics of particle motion (all of which probably exist to some extent in the interplanetary region), it is important to obtain and study detailed information on the modulation of the galactic cosmic radiation, including measurements of the form of the modulation for different charge com-

ponents not only at the earth but also at other locations in the solar system. Our results suggest that no single effect dominates over the extended rigidity range, although we feel that a general diffusion process, in which some form of diffusive deceleration occurs, may be an important factor producing the eleven-year modulation.

Finally, it is worth while to compare our results with those of other observers, particularly those for the period after 1959 when our measurements ceased. Comparing α particles first, we note that in the period 1955–1959 the low rigidity differential α-particle spectra over the range 1 to 3 bv measured by the Cerenkov scintillation counter technique and photographic emulsions are in essential agreement within the experimental errors, usually approximately 20 per cent. Furthermore, the intensity of these low rigidity α particles is uniquely related to the counting rates of high latitude neutron monitors during this period.

In Figure 7 we show the differential α-particle spectrum measured on July 7, 1961, by *Fichtel et al.* [1964] using emulsions. The lower dashed curve is the spectrum that would be predicted by the Cerenkov scintillation counter for July 7, 1961, on the basis of the observed neutron monitor intensities and the regression curve established during the 1955–1959 period. Thus it appears that the recovery of this component is proceeding in a manner compatible with the features established during the period 1955–1959.

Turning now to the protons, we note that no measurement comparable to ours is available on low rigidity protons (e.g. <2 bv) during the period 1955–1959. Recently a number of measurements have been made on low rigidity protons by both counter techniques and emulsions. Comparable measurements were made with these techniques during July–August 1961 [*Meyer and Vogt*, 1963; *Fichtel et al.*, 1964]. Their results, shown in Figure 7, can be directly compared with the α-particle spectrum also given in Figure 7 (see also Table 1). These results cover the range 0.4–0.8 bv and appear to be in general agreement, except that they appear to diverge at low rigidities. Since they are at rigidities less than 0.8 bv, the region of comparison with our result is not large, although some reasonable and interesting comparisons can be made. First, although the rigidity ranges for protons and α particles do not overlap in any one experiment, it appears that, for a reasonable extension of the proton spectrum measured below 0.8 bv in 1961, there is a definite excess of protons relative to the measurements of α particles above 1 bv reported here and to the emulsion measurements as well. Such an excess might be expected in a number of models for the long-term modulation, although the relative excess of protons as a function of rigidity is quite different from that which would be predicted by any of these models. Second, the intensity of protons measured by *Meyer and Vogt* [1963] or *Fichtel et al.* [1964] at 0.8 bv is comparable to our intensity at this rigidity measured at a time when the high latitude neutron monitor rate was 9 per cent higher than in the July–August 1961 period. We do not believe the intensity we have measured at this rigidity is depressed because of geomagnetic cutoff effects. If this discrepancy is real, it may indicate the presence of an unusual modulation of galactic protons at low rigidities during the period of decreasing solar activity or the possibility that excess solar protons at low rigidities are contained in the interplanetary field for long periods [*Vogt*, 1962; *Meyer and Vogt*, 1963]. It will take further definitive measurements on the low rigidity proton and α-particle spectra to decide these problems.

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